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Design, testing, and modelling of a novel robotic system for trans-esophageal ultrasound

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ABSTRACT

Background: Trans-esophageal echocardiography (TEE) has been widely utilized for cardiac disease diagnosis and interventional procedure guidance. However, the TEE operator is required to manually manipulate the probe, often for long periods of time and sometimes in an X-ray environment where there is exposure to ionising radiation.

Methods: A novel robotic manipulation system for remote control of commercial TEE probes has been developed and tested. The system has four degrees of freedom (DOF) and characterized by a kinematic model. The accuracy of the model and the error propagation were analysed.

Results: The prototype system was shown to exhibit the required function in terms of the mechanical reliability and range of motion. The forward kinematic model can accurately predict the trajectory of the probe tip movement. The average point to point error was 2.60mm and 3.55°.

Conclusions: Robotic assistance provided by the proposed system may improve the TEE operating environment. The proposed forward kinematic model can be further employed for automatic control.

INTRODUCTION

Trans-esophageal echocardiography (TEE) is a type of echocardiograph in which the ultrasound transducer, positioned on a specialized probe, is guided via the oral cavity into the esophagus. TEE scanning, which is considered a semi-invasive procedure, should be performed by a trained echocardiographer (1). Since the TEE probe is inserted into the esophagus, which passes immediately posterior to the heart, the ultrasound beam travels a short distance before accessing the heart structures. This minimizes the attenuation of the ultrasound signal, resulting in stronger return signals. The short penetration depth between the esophagus and the heart also enables TEE to use increased frequency transducers, which yield better spatial resolution (2).

Since TEE was introduced over a decade ago, this technique has rapidly become a powerful tool to assess the cardiac anatomy and function (3). Generally, TEE is used to visualize the anatomy of the heart and thoracic aorta, and assess the global and regional cardiac function in order to detect and evaluate cardiac disease (2). For example, TEE can be used to evaluate native valve disease, prosthetic valve function, congenital heart disease and hemodynamic instability of intensive care patients. It can also be used to detect aortic disease, potential etiologies of stroke and complications of endocarditis.

TEE is used not only as a diagnostic tool but also as a monitoring adjunct for operative and percutaneous cardiac procedures. One of the strongest indications for TEE is evaluation of the mitral valve during repair (4). TEE also plays an important role during left ventricular assist device (LVAD) implantation and coronary artery bypass graft (CABG) (5, 6). Many congenital heart diseases can be treated with catheter-based approaches and TEE improves the safety and success of many of these procedures (7).

Despite the wide use of TEE, there are still many challenges when handling the TEE probe for the cardiologist:

1) Many cardiac procedures are usually accompanied by X-ray fluoroscopy imaging and in a typical setup, the TEE operator is required to stand close to the path of the X-rays (8). Though radiation protective clothing is required, up to 10% of the radiation from X-ray is still able to pass through the shielding (9). This is not ideal for the duration of the longer procedures, since chronic exposure to ionizing radiation is known to cause cataracts, leukemia and several other types of cancer (10).

2) The X-ray protective clothing for the TEE operator, including an apron and thyroid shield, can cause orthopedic injuries due to the accumulated effects of bearing the weight (11). This has been labeled as “interventionalist’s disc disease” by prior authors to draw attention to this distinct occupational hazard (12).

3) One of the barriers to the greater utilization of TEE is the need for advanced training. Like any technology that requires human interpretation, there is also a degree of user variability with the results of TEE.

With the development of medical robotic technologies, ultrasound robotic systems have been employed in various situations as replacements for the traditional human-operated ultrasound system. An ultrasound robotic system can provide accurate operation with good repeatability and reliability, serving as a replacement for the human hand. It can also be incorporated with other imaging techniques to deliver intelligent solutions in many clinical situations. Considering the current challenges of TEE, a robotic TEE manipulator with intelligent functions that can operate the TEE probe remotely controlled by the operator would be a revolutionary design in the field of echocardiography.

Several researchers working on intra-rectal ultrasound robots have demonstrated the feasibility of using a robotized 3-D ultrasound probes in robot assisted prostate imaging and intervention (13-15). A catheter robotic system for intra-cardiac echocardiography (ICE) was proposed by Loschak *et al.* (16). Their research focused on motorizing four actuated degrees of freedom and automatically acquiring the image target. Other types of robotic systems for manipulating a flexible endoscope similar to a TEE probe have been proposed by other researchers for different clinical applications. Endoscopic robots for natural orifice transluminal endoscopic surgery (NOTES) have been proposed by different groups for master-slave control and tracking of a region of interest (17, 18). A motorized hand-held flexible rhino endoscope in ear-nose-and-throat diagnoses was proposed for image-guided steering (19). However, these endoscope systems are not suitable to control the TEE probe because the structure and the steering methods are different.

We have developed the first robotic trans-esophageal ultrasound prototype to remotely operate a commercial TEE probe via a robotic probe holder and several remote control mechanisms (20). In this paper, we present the detailed design and construction methods of the TEE robot. Once the probe is placed in the esophagus, this robotic system allows the TEE operator to precisely adjust the probe's position using a PC interface or a standard gamepad, enabling TEE use for longer periods in a zero radiation environment. Apart from remote manual control, we are also interested in helping the cardiologist to deskill the TEE procedure by employing automatic control. To this end, we present a forward kinematic model of the TEE robot which relates the motor parameters to the TEE ultrasound image outputs. The model is validated with the Optotrak measurement system (Northern Digital Inc.) in terms of the targeted accuracy and the propagation of the resulting error in the ultrasound image space.

MATERIAL AND METHODS

Robotic TEE system design

1) Standard TEE probe

A standard TEE probe comprises a flexible gastroscope tube with a miniature transducer mounted on its tip. The echocardiographer can precisely control the position and orientation of the imaged region by manipulating five degrees of freedom (DOFs) of the probe, as follows (see Fig. 1): (a) The probe can be advanced or withdrawn in the esophagus by gripping the probe shaft and moving along its long axis. (b) The orientation can be controlled by manually rotating the probe handle along its long axis. (c, d) Two coaxial knobs on the probe handle adjust the orientation of the probe tip, one for left-right steering and one for anteflex-retroflex steering. (e) The orientation of the ultrasound beam can be electronically steered by a button control on the probe handle.

2) Static System Description

The add-on robot holds the probe handle and manipulates four of the five DOFs that are available in manual handling of the probe. Manipulation of the electronic steering buttons is not yet implemented and is not required when operating in 3D mode. The robot comprises three structures, as shown in Fig. 2: the handle control structure providing two DOFs to rotate the knobs; a one-DOF probe rotation mechanism to rotate the whole probe together with the handle control structure; and a final one-DOF structure providing linear translation of the probe and all other structures. The handle control structure consists of two rotational wheels precisely formed to mate with and drive the two knobs on the TEE probe handle via belt mechanisms. Magnetic sensing devices are embedded into the wheels to track the initial home or neutral position at which the TEE probe is inserted. The probe rotation structure consists of a gear train mechanism driven by a balanced two-motor design. The final translation structure uses a linear belt and rail system.

3) Implementation of the system design

The implementation of this new add-on manipulator was based on a standard TEE probe (X7-2t, Philips Medical Systems, Andover, MA). The probe can be clipped into the manipulator (Fig. 3). The manipulator was designed in CAD-software and produced through rapid prototyping (3D printing) and machining. The overall rotation diameter of the handle control structure is 110 mm. The dimensions of the whole robot are $500 \times 210 \times 40$ mm.

The robot utilizes five stepper motors (NEMA 17, 5V, 1.2A). Two of the stepper motors for the steering mechanism are controlled by a single-board microcontroller with an operating frequency of 16 MHz (Arduino Nano). The Arduino Nano is embedded into the handle control structure with a Bluetooth module (HC-06, 10 metres range), magnetic sensors and a voltage regulator attached (Fig. 4). The whole handle control piece is a wireless individual device powered by a rechargeable battery pack. The other three motors for rotation and translation mechanisms are separately controlled by another microcontroller (Arduino Nano).

4) Control of the system

The control of the robot is based on a master-slave configuration. A PC works as the master device and two Arduino-Nano microcontrollers, integrated into the handle control structure and the rail structure, are used as the slave processors. The PC runs a user interface software written in C#, which communicates with the Arduino via a custom protocol. The interface software provides the ability to individually control the four DOFs. The software can also be interfaced with other control devices connected to the PC, using Microsoft DirectX 9.0 SDK to map physical buttons to motor control commands. This allows the possibility of a separate control approach in which the TEE robot is controlled wirelessly. The current implementation allows a gamepad or joystick, although any custom-made control device is feasible.

Modelling of the system

The forward kinematic model of the flexible rhino endoscope is the basis of the continuum robot control. Different approaches have been utilized to derive the forward kinematic model. Camarillo *et al*. used a mechanical approach to model the tendon-driven continuum manipulators with an application to a steerable cardiac catheter (21). Other researchers also employed the modified Denavit-Hartenberg approach by investigating multi-section articulation parameters (22). Another approach was based on geometric principles and the classic coordinate transformation technique. In (17), a bi-directional bending tip was modelled for the application of NOTES. A similar method of geometry modelling was also employed in modelling the intra-cardiac echocardiography catheter (16).

1) Forward kinematic model

In our TEE probe model, we employ the geometry approach (also known as the constant curvature model) with two assumptions. First, we assume that the overall bending is independent of the order in which the individual bends in the two directions are applied. Second, plastic torsion is neglected so that the probe tip can only bend in the bending plane. Our forward kinematic model uses the input of the TEE probe handle to calculate the orientation and position of the probe tip, where the ultrasound transducer is embedded. The four inputs of the model are listed below:

1. The rotation angle of the bending knob, φ_y about the Y-axis, which controls the bending tip pitch in the posterior-anterior plane. φ_y is also the rotation angle of the pulley inside the probe;
2. The rotation angle of the bending knob, φ_x about the X-axis, which controls the bending tip yaw in the left-right plane. φ_x is also the rotation angle of the pulley inside the probe;
3. The rotation angle of the probe handle, φ_z about the Z-axis, which controls rotation of the whole probe;
4. The translation distance of the probe handle, d_z along the Z-axis, which controls translation of the whole probe.

The ratio of bending about the Y-axis to bending about the X-axis, α, is the angle between the bending plane and the X-Z plane (Fig. 5 (a)).

$$\alpha = \tan^{-1}\left(\frac{\varphi_x}{\varphi_y}\right) \quad (1)$$

Previous research has shown that a continuum robot with two bending directions follows a curve of constant radius of curvature along the flexible part of the device (23). A rotation of angle φ_x or φ_y of a pulley changes the distribution of the length along the flexible part. The changes of length of the pull wires are δ_1 and δ_2.

$$\delta_1 = \varphi_x . R_p , \quad \delta_2 = \varphi_y . R_p \quad (2)$$

where R_p is the radius of the pulley inside of the probe where the pull wires are attached. The bending angle β in the bending plane is

$$\beta = \sqrt{(\frac{\delta_1}{R_t})^2 + (\frac{\delta_2}{R_t})^2} \quad (3)$$

where R_t is the cross-sectional radius of the TEE probe tip. The radius of curvature due to the two-direction bending is

$$R = \frac{L_f}{\beta} \quad (4)$$

where L_f is the length of the bending section of the probe tip. The probe comprises a flexible part that follows this curvature model, with a rigid extension to the probe tip on the end. The translation from the base coordinate frame to the tip coordinate frame can be obtained from the orthogonal projection in the bending plane, as shown in Fig. 5 (b). The translation matrix is shown below:

$$\mathbf{t}_{bend} = \begin{bmatrix} R(1-\cos\beta)\cos\alpha + L_u \sin\beta\cos\alpha \\ R(1-\cos\beta)\sin\alpha + L_u \sin\beta\sin\alpha \\ R\cdot\sin\beta + L_u\cos\beta \end{bmatrix} \quad (5)$$

where L_u is the length of the rigid section of the probe tip. The tip orientation from the base frame to the tip frame can be calculated by Rodrigues' rotation formula (24) which transforms all three basis vectors to compute a rotation matrix from an axis-angle representation.

$$\mathbf{R} = \mathbf{I} + \sin\beta\cdot[\mathbf{k}]_\times + (1-\cos\beta)[\mathbf{k}]_\times^{\,2} \quad (6)$$

The rotation axis (unit vector) **k** is orthogonal to the bending plane. In the matrix notation form of the Rodrigues' formula, $[\mathbf{k}]_x$ denotes the antisymmetric matrix with entries

$$[\mathbf{k}]_\times = \begin{bmatrix} 0 & -k_z & k_y \\ k_z & 0 & -k_x \\ -k_y & k_x & 0 \end{bmatrix} \quad (7)$$

The rotation angle about the new axis **k** is β. Therefore, the rotation matrix $\mathbf{R}_{bend}$ is

$$\mathbf{R}_{bend} = \begin{bmatrix} k_x^2 V_\beta + C_\beta & k_x k_y V_\beta - k_z S_\beta & k_x k_z V_\beta + k_y S_\beta \\ k_x k_y V_\beta + k_z S_\beta & k_y^2 V_\beta + C_\beta & k_y k_z V_\beta - k_x S_\beta \\ k_x k_z V_\beta - k_y S_\beta & k_y k_z V_\beta + k_x S_\beta & k_z^2 V_\beta + C_\beta \end{bmatrix} \quad (8)$$

where S_x, C_x, and V_x denote sin(x), cos(x), and (1-cos(x)) respectively. According to Fig. 5, the normal unit vector **k** to the bending plane can be expressed as ($\mathbf{k}$=-sin $\alpha\mathbf{i}$ + cos$\alpha\mathbf{j}$). The rotation matrix $\mathbf{R}_{bend}$ can therefore be written as:

$$\mathbf{R}_{bend} = \begin{bmatrix} S^2{}_\alpha + C_\beta C^2{}_\alpha & -S_\alpha C_\alpha V_\beta & C_\alpha S_\beta \\ -S_\alpha C_\alpha V_\beta & C^2{}_\alpha + C_\beta S^2{}_\alpha & S_\alpha S_\beta \\ -C_\alpha S_\beta & -S_\alpha S_\beta & C_\beta \end{bmatrix} \quad (9)$$

A 4×4 transformation matrix, $\mathbf{T}_{bend}$ is then derived to bend the TEE tip with respect to the base. The translation matrix and rotation matrix of the handle are straightforward, denoted as $T_{trans}(d_z)$ and $T_{rot}(\varphi_z)$. The bending of the tip is calculated relative to the fixed base frame after translation and rotation of the handle, resulting in the final position of the tip frame relative to the initial robot frame:

$$\mathbf{T}_{tip} = T_{trans}(d_z)\bullet T_{rot}(\varphi_z)\bullet T_{bend}(\varphi_x, \varphi_y) \quad (10)$$

2) Calibration of TEE tip

The TEE calibration procedure aims to determine the transformation from the TEE tip coordinate to the ultrasound image coordinate. Our previous work described in (25) has determined the transformation from the coordinates of a nano-CT image of the probe to the ultrasound image coordinate. The nano-CT volume (Fig. 6) provides a precise 3D model of the TEE probe tip, which can then be related to the model described above. The nano-CT has its own coordinate system with coordinate directions aligned to the voxels. The coordinate origin is at the centre of the voxel array of the nano-CT image, which is a point (approximately along the centre line of the probe tip) located in the rigid section of the TEE probe tip. The voxel size of the nano-CT volume is 0.2 mm in all directions.

The transformation from the ultrasound image coordinate to the nano-CT coordinate (Fig. 6) is made up of a the following transformations:

1. T_1 is the transformation from the nano-CT coordinates to the ultrasound cone tip coordinates, which is already known from the previous work (25). Since the nano-CT coordinate origin is in the rigid section of the TEE probe tip, this transformation remains the same for different bending inputs.
2. T_2 is a Z-axis rotation by the angle set for the electronic steering controlled by the buttons on the TEE probe handle.
3. T_3 is a translation from the cone tip coordinate origin to the ultrasound image coordinate origin. The default is to use the image centre as the image coordinate origin, with the same orientation as the steered cone-tip coordinates.

The forward kinematic model can predict any ‘local tip coordinate’ as described in the previous section. Therefore, it can predict the nano-CT coordinates and give the transformation from nano-CT coordinates to base coordinates. In summary, The overall transformation from ultrasound image coordinates to base coordinates is shown below:

$$^{Base}\mathbf{T}_{us\_image} = {}^{Base}T_{nano\_CT} \bullet T_1 \bullet T_2 \bullet T_3 \quad (11)$$

Experimental methods

In this section, we present experimental methods with an Optotrak measurement system to assess the properties of the robotized TEE system and evaluate the mechanical assumptions of the forward kinematic model. We also propose a quantitative analysis method based on the Optotrak measurement system to assess the targeted accuracy of the forward kinematic model and the error propagation effect in the ultrasound cone space. Considering the formation of the forward kinematic model, the bending transformation is the segment that is most likely to cause error due to the mechanical assumptions and the inaccuracy of the constant curvature model itself. In comparison, the rotation and translation of the handle are well modelled by simple rotation and translation transformations, and can be treated as accurate segments of the model. Therefore, we focus our experiments on validating the bending transformation.

The Optotrak measurement system used in the following experiments has its own world coordinate, reference coordinate and tracking coordinate systems. It reports transformations of the tracking coordinate system relative to a fixed reference coordinate, attached to the table. We first define several coordinate systems used in the quantitative analysis. The definitions of these coordinates with explanations are as follows (the first three of them are shown in Fig. 7):

{Base}: the origin is at the bending origin of the probe tip. The base coordinate is fixed, which provides a world coordinate for the analysis.

{Nano-CT}: the origin is at the centre of the voxel array of the nano-CT image, which is a point (approximately along the centre line of the probe tip) located in the rigid section.

{Cone}: the origin is at the ultrasound cone tip. For simplicity, the electronic steering of the ultrasound beam is zero in our analysis.

{Optotrak}: the reference coordinate of the Optotrak system. The definition is arbitrary but fixed during the experiment.

{Plate}: the tracking coordinate of the Optotrak, fixed to the rigid part of the probe. The axes definition is arbitrary, but the origin is at the mass centre of the tracking body.

1) Repeatability of the robotic system

In the first experiment, we performed a repeatability test in order to assess the properties of the robotized TEE system. The primary goal of this experiment was to assess the reliability of the mechanical and electronic design of the robot system. This can be verified by investigating the probe tip position when the same sets of motor parameters are given. The experimental setup is shown in Fig. 8. The robotic TEE system was placed on a desk with the TEE probe inserted. The flexible gastroscope section of the TEE probe was constrained using a guide tube. The Optotrak system was employed to measure the position and orientation of the TEE probe tip. A rigid tracking body (**{Plate}** coordinates) was attached at the rigid section of the probe tip and used for validation.

During the experiment, we controlled the robotic system via a computer, which steered the tip of the probe in two planes, rotated the probe about its shaft, and translated the probe along the rail. For each of the steering processes, the bending tip was curved from -40 degrees to +40 degrees with a difference of 4 degrees in each step. For the rotation and translation processes, the probe was rotated 0 degrees to 360 degrees with a difference of 18 degrees in each step and translated from the initial position to 50cm with steps of 2.5cm. For each of the axes, the measurement processes were repeated 4 times (N=84) to acquire the repeatability performance of the robotic system. Each set of data (N=21) for one axis was compared with the other three sets. For the same motor inputs, the differences of the orientation and position outputs between different sets were defined as orientation and position errors.

2) Validation of the plastic torsion and joint coupling

In the forward kinematic model, we assume that the effect of the plastic torsion is negligible and that the TEE tip can only bend in the bending planes. This experiment aimed to assess the effect of plastic torsion in the TEE bending process to evaluate the assumption of the forward kinematic model. We used the same experimental data from the first experiment and quantified the off-plane distance. In the Optotrak coordinate system, we defined the bending plane from the measured data by utilizing any of the two vectors, e.g. the first, central, and last measured points. For each of the measured points, the distance from the point to the defined bending plane was calculated.

The forward kinematic model also assumes that the order of knob actuation does not affect the final TEE tip position. To validate this assumption, a further experiment using the Optotrak system was performed. During the experiment, the first knob remained constant while the second knob was actuated by the TEE robot, and then the first knob was incremented while the second knob remained constant throughout the workspace. Each set of corresponding points (with the same motor inputs but different order for knob actuation) was then compared.

3) Targeted accuracy of the forward kinematic model

For each of the bending inputs, the forward kinematic model gives the transformation from **{Nano-CT}** to **{Base},** which is denoted as ${}^{Base}T_{Nano\text{-}CT}$. This transformation matrix can then be decomposed to give the transformation parameters: θ_x, θ_y, θ_z, t_x, t_y, t_z. θ_x, θ_y, θ_z are the Cardan angles referring to rotations about the X-, Y- and Z-axes, respectively. t_x, t_y, t_z are the translation distances in the X-, Y- and Z-axes.

For the same bending inputs, we then aim to find the transformation from **{Nano-CT}** to **{Base}** from the real Optotrak measurement result, which is denoted as ${}^{Base}T_{Nano\text{-}CT}(measured)$. Fig. 9 shows the experimental setup and the following steps describe the processing method.

1. Transformation from **{Nano-CT}** to **{Plate}**: the position of four corresponding points (e.g. four corners of the transducer face) in both **{Plate}** and **{Nano-CT}** were acquired respectively. The Optotrak pointer was pivot calibrated, and was then utilized to pick up the four corners of the TEE transducer face, defining four points in **{Plate}**. The positions of these points in **{Nano-CT}** were acquired using the Nano-CT volume image. The transformation ${}^{Plate}T_{Nano\text{-}CT}$ was then derived using least-squares estimation (26). The rigid tracking body was tightly attached onto the rigid section of the probe tip, so this transformation remains fixed.
2. Transformation from **{Optotrak}** to **{Base}**: this transformation remains the same for different bending inputs as both coordinates are fixed. We used the neutral position (when the probe tip is straight) to estimate the ${}^{Base}T_{Optotrak}$:

$$ {}^{Base}T_{Optotrak} = {}^{Base}T_{Nano-CT}(neutral) \bullet {}^{Nano-CT}T_{Plate} \bullet {}^{Plate}T_{Optotrak}(neutral) \quad (12) $$

The ${}^{Base}T_{Nano\text{-}CT}(neutral)$ can be obtained from the forward kinematic model, since the constant curvature model is accurate in the neutral position when no bending occurs. ${}^{Nano\text{-}CT}T_{Plate}$ was obtained in the first step. ${}^{Plate}T_{Optotrak}(neutral)$ can be obtained from the Optotrak measurement when placing the probe tip in its neutral position.

3. Transformation from **{Nano-CT}** to **{Base}** from the measurement data: for each of the bending inputs, the Optotrak reports the transformation from the tracking coordinate (**{Plate}** coordinates) to the reference coordinate (**{Optotrak}** coordinates), which is ${}^{Optotrak}T_{Plate}$. The transformation ${}^{Base}T_{Nano\text{-}CT}(measured)$ can be then calculated:

$$ {}^{Base}T_{Nano-CT}(measured) = {}^{Base}T_{Optotrak} \bullet {}^{Optotrak}T_{Plate} \bullet {}^{Plate}T_{Nano-CT} \quad (13) $$

Therefore, we can then decompose the resulting matrix to give the transformation parameters: θ_x', θ_y', θ_z', t_x', t_y', t_z' with the same method as described previously. Eventually, the probe tip was driven bi-directionally by the PC. For each of the knobs, the stepper motor was driven from -2000 steps to +2000 steps with a 200 step division, which covered most of the working space of the bending. For each position, the targeted accuracy of the forward kinematic model can be quantified by comparing the ${}^{Base}T_{Nano\text{-}CT}(measured)$ and ${}^{Base}T_{Nano\text{-}CT}$. The distance error and the orientation error are defined respectively as follows:

$$ dis\_error = \sqrt{(t_x' - t_x)^2 + (t_y' - t_y)^2 + (t_y' - t_y)^2} \quad (14) $$

$$ orien\_error = \sqrt{(\theta_x' - \theta_x)^2 + (\theta_y' - \theta_y)^2 + (\theta_y' - \theta_y)^2} \quad (15) $$

4) Ultrasound image error propagation

The TEE image error caused by the inaccuracy of the forward kinematic model will be propagated with regard to the distance from the transducer. The inaccurate prediction of the orientation and position of the TEE tip can potentially create a considerable error in the ultrasound image, especially for a target object at the far side of the ultrasound cone. In this section, we propose a quantitative method to evaluate the error propagation due to the inaccuracy of the forward kinematic model.

In the previous section, we described the transformation from the **{Nano-CT}** to **{Base}** for the theoretical model and the measurement respectively. For simplicity, we utilized the cone coordinate as the ultrasound image coordinate in the experiment. The overall transformation from the ultrasound image coordinate to the base coordinate is

$$ {}^{Base}T_{US-image} = {}^{Base}T_{Nano-CT} \bullet {}^{Nano-CT}T_{US-image} \quad (16) $$

$$ {}^{Base}T_{US-image}(measured) = {}^{Base}T_{Nano-CT}(measured) \bullet {}^{Nano-CT}T_{US-image} \quad (17) $$

We then defined the points in the ultrasound image by assuming an image size (e.g. 90 deg * 90 deg cone, 15 cm depth). The ultrasound cone tip was assumed to be the image coordinate centre. Ten image planes were selected within the TEE field of view (FOV) which were parallel to the transducer of the TEE probe (Fig. 10). The interval between two planes was 15mm. The landmarks were defined on the four corners of the image planes. The point locations relative to the cone tip are denoted as P_cone. For each set of motor settings, we applied the following transformation:

$$ {}^{Base}P\_cone = {}^{Base}T_{US-image} \bullet {}^{US-image}P\_cone \quad (18) $$

This calculates the positions of the landmarks relative to the base coordinate system using the forward kinematic model. The same idea of transformation was applied to calculate the landmark positions relative to the base coordinate system using the Optotrak measured data:

$$ {}^{Base}P\_cone(measured) = {}^{Base}T_{US-image}(measured) \bullet {}^{US-image}P\_cone \quad (19) $$

The potential TEE image error at different depths was then assessed by calculating the mean position errors of the landmarks.

RESULTS

Repeatability of the robotic system

The results of the repeatability experiments are summarized in Table I. It shows the mean and standard deviation of the error over all the points for each axis.

Validation of the plastic torsion and joint coupling

For the validation of the plastic torsion, the results show that for each bending axis, the mean off-plane distances are 0.14mm and 0.21mm respectively. The maximum off-plane distances are 0.57mm and 0.27mm respectively. According to our experimental method for joint coupling validation, each set of corresponding points was compared and it was determined that the maximum distance between two corresponding points was within 1 mm.

Targeted accuracy of the forward kinematic model

For each of the measurements, the motor parameters were input into the forward kinematic model. The predicted nano-CT coordinates (origin position and orientation), i.e. ${}^{Base}T_{Nano\text{-}CT}$, as described previously were calculated. The measured data were processed by applying the method proposed in the previous section to calculate the ${}^{Base}T_{Nano\text{-}CT}(measured)$. Fig. 11 shows the comparison of the measured positions of the nano-CT coordinate origin in base coordinates and the positions in the same coordinate system predicted using the stepper motor steps and the forward kinematic model. The point-to-point errors were quantitatively assessed for position and orientation using the method proposed previously. The mean and standard deviation of the error over all the points are summarized in Table II.

Ultrasound image error propagation

For each measurement, the positions of the landmarks defined in the pyramid FOV relative to the base coordinate were calculated using the method described in the previous section. This was compared with the predicted position of the landmarks based on the forward kinematic model. The mean distance errors were calculated for different ultrasound penetration depths. Fig. 12 and Fig. 13 show the mean distance error of the landmarks for different penetration depths and different bending angles of the knobs. The result shows the error is increased from 1.2 millimetres (minimum) to 19 millimetres (maximum) with increasing penetration depth.

DISCUSSION

In this paper, we have presented a new concept and prototype to manipulate a standard TEE probe. Our primary goal was to provide the cardiologist a remote control approach for the standard TEE scanning so they can work in a zero radiation environment with a comfortable posture for the duration of long cardiac procedures. We have described the design and implementation of the proposed system, which is the first TEE robotic system introduced. The current implementation manipulates four of the five DOFs of the manual TEE controls. A mechanism for the remaining electronic steering DOF was not included in this preliminary prototype. Future design iterations will incorporate this feature. The described system is lightweight and has a small footprint with all the electronics and control devices built in. The handle control piece for knob control can work stand alone for individual purposes. The proposed driving mechanism can easily be adapted to work with other types of TEE probe on the market by simply changing the shape and dimension of the structure. In addition, the proposed add-on system doesn't change any internal structure of the standard TEE probe. The TEE probe can be easily removed from the robotic system, switching back to manual control mode if necessary.

We have performed preliminary bench testing of the system sufficient to verify the correct working of the mechanism and controls. We have determined that the repeatability error of the robotic system is less than 1mm. Comparing to the workspace of the TEE probe tip, which is a half sphere with 40mm radius, the evaluation of the entire data indicates the driving mechanism and electronics of the designed robotic system are reliable and the repeatability of the probe tip position and orientation is therefore acceptable. We have evaluated two mechanical assumptions of the forward kinematic model. The experimental results indicate that plastic torsion and the pull wire coupling have a minimal effect on the system.

Ultimately, we expect the system to have uses beyond just remote control. We proposed a forward kinematic model of the TEE robotic system based on the constant curvature model. The theoretical and practical behaviors of the TEE probe were analyzed. The forward kinematic model was then extended into the ultrasound image coordinates using the calibration result of the TEE probe tip. The error propagation in the ultrasound FOV was then assessed. The results from the experiments show that the forward kinematic model provides a good representation of the workspace of the TEE robotic system. The predicted trajectory from the forward kinematic model can accurately predict the TEE probe tip movement. The errors mainly account for the initial approximations of the forward kinematic model; namely, there are nonuniformities along the TEE probe bending tip section. Additionally, the origin of the nano-CT coordinate system is not exactly along the centre line of the probe tip. The approximation used in this paper also contributes to the errors. As for the point-to-point error, this is mainly accounted for by the hysteresis effect due to the backlash in the TEE system. We also noticed that the TEE probe has an inherent dead zone when the bending knobs cross the zero point due to the lack of tension in the pull wires. For our experiment where the TEE tip bent in the default two directions (left-right and anteflex-retroflex steering), the dead zone ranged over roughly ±10° in which rotating the bending knobs resulted in no output.

Future work will be focused on the automatic control of the TEE probe tip by using visual servo control, i.e. ultrasound image feedback. We intend to develop an automatic view planning approach in which the probe is automatically driven to an appropriate location in response to the user requesting a particular view of the heart. We also want to provide a more intuitive control method for the TEE robot, e.g. a dummy probe with the same structure of the TEE probe. We'll then obtain clinical feedback from cardiologists on the control mechanism, control software, and general usability. In terms of patient safety, although major complications of TEE are rare (<0.02%) (27), further experiments in cadavers are still required to detect and fine-tune the force safety limits. To further improve the safe use of the TEE robot, we intend to develop an eject mechanism for the robot, which enables the user to release the probe from the mechanism immediately by pressing a single button on the robot. This will actuate another motor ejecting the probe from the manipulator.

Conflict of Interest

The authors declare that there are no conflicts of interest.

REFERENCE

1. Otto CM. The Practice of Clinical Echocardiography: W.B. Saunders; 2002.
2. Peterson GE, Brickner ME, Reimold SC. Transesophageal Echocardiography: Clinical Indications and Applications. Circulation. 2003 May 20;107(19):2398-402.
3. Shanewise JS, Cheung AT, Aronson S, Stewart WJ, Weiss RL, Mark JB, et al. ASE/SCA guidelines for performing a comprehensive intraoperative multiplane transesophageal echocardiography examination: recommendations of the American Society of Echocardiography Council for Intraoperative Echocardiography and the Society of Cardiovascular Anesthesiologists Task Force for Certification in Perioperative Transesophageal Echocardiography. Anesthesia and analgesia. 1999 Oct;89(4):870-84.
4. Lambert AS, Miller JP, Merrick SH, Schiller NB, Foster E, Muhiudeen-Russell I, et al. Improved evaluation of the location and mechanism of mitral valve regurgitation with a systematic transesophageal echocardiography examination. Anesthesia and analgesia. 1999 Jun;88(6):1205-12.
5. Kapoor PM, Chowdhury U, Mandal B, Kiran U, Karnatak R. Trans-esophageal echocardiography in off-pump coronary artery bypass grafting. Annals of cardiac anaesthesia. 2009 Jul-Dec;12(2):167.
6. Scalia GM, McCarthy PM, Savage RM, Smedira NG, Thomas JD. Clinical utility of echocardiography in the management of implantable ventricular assist devices. Journal of the American Society of Echocardiography : official publication of the American Society of Echocardiography. 2000 Aug;13(8):754-63.
7. Miller-Hance WC, Silverman NH. Transesophageal echocardiography (TEE) in congenital heart disease with focus on the adult. Cardiology clinics. 2000 Nov;18(4):861-92.
8. McIlwain EF, Coon PD, Einstein AJ, Mitchell CKC, Natello GW, Palma RA, et al. Radiation Safety for the Cardiac Sonographer: Recommendations of the Radiation Safety Writing Group for the Council on Cardiovascular Sonography of the American Society of Echocardiography. Journal of the American Society of Echocardiography. 2014;27(8):811-6.
9. Bushberg JT. The Essential Physics of Medical Imaging: Lippincott Williams & Wilkins; 2002.
10. Brenner DJ, Doll R, Goodhead DT, Hall EJ, Land CE, Little JB, et al. Cancer risks attributable to low doses of ionizing radiation: Assessing what we really know. Proceedings of the National Academy of Sciences. 2003 November 25;100(24):13761-6.
11. Ross AM, Segal J, Borenstein D, Jenkins E, Cho S. Prevalence of spinal disc disease among interventional cardiologists. The American journal of cardiology. 1997 Jan 1;79(1):68-70.
12. Goldstein JA, Balter S, Cowley M, Hodgson J, Klein LW. Occupational hazards of interventional cardiologists: prevalence of orthopedic health problems in contemporary practice. Catheterization and cardiovascular interventions : official journal of the Society for Cardiac Angiography & Interventions. 2004 Dec;63(4):407-11.
13. Chunwoo K, Schafer F, Doyoung C, Petrisor D, Misop H, Stoianovici D, editors. Robot for

ultrasound-guided prostate imaging and intervention. Intelligent Robots and Systems (IROS), 2011 IEEE/RSJ International Conference on; 2011 Sept 25-30.

14. Fichtinger G, Fiene JP, Kennedy CW, Kronreif G, Iordachita I, Song DY, et al. Robotic assistance for ultrasound-guided prostate brachytherapy. Medical image analysis. 2008 Oct;12(5):535-45.
15. Yu Y, Podder TK, Zhang YD, Ng WS, Misic V, Sherman J, et al. Robotic system for prostate brachytherapy. Computer aided surgery : official journal of the International Society for Computer Aided Surgery. 2007 Nov;12(6):366-70.
16. Loschak PM, Brattain LJ, Howe RD, editors. Automated pointing of cardiac imaging catheters. Robotics and Automation (ICRA), 2013 IEEE International Conference on; 2013 May 6-10.
17. Ott L, Nageotte F, Zanne P, de Mathelin M. Robotic Assistance to Flexible Endoscopy by Physiological-Motion Tracking. Robotics, IEEE Transactions on. 2011;27(2):346-59.
18. Phee SJ, Low SC, Huynh VA, Kencana AP, Sun ZL, Yang K. Master and slave transluminal endoscopic robot (MASTER) for natural orifice transluminal endoscopic surgery (NOTES). Conference proceedings : Annual International Conference of the IEEE Engineering in Medicine and Biology Society IEEE Engineering in Medicine and Biology Society Annual Conference.2009:1192-5.
19. Chen F, Weiwei S, Gumprecht JDJ, Strauss G, Lueth TC, editors. Image-guided steering of a motorized hand-held flexible rhino endoscope in ENT diagnoses. Robotics and Biomimetics (ROBIO), 2012 IEEE International Conference on; 2012 Dec 11-14.
20. Wang S, Housden J, Singh D, Althoefer K, Rhode K. Development of a Robotic Trans-esophageal Ultrasound Probe Manipulator. Design of Medical Devices Conference; 2014 Oct 22-24; The Netherlands. p. 96-7.
21. Camarillo DB, Milne CF, Carlson CR, Zinn MR, Salisbury JK. Mechanics Modeling of Tendon-Driven Continuum Manipulators. Robotics, IEEE Transactions on. 2008;24(6):1262-73.
22. Jones BA, Walker ID. Kinematics for multisection continuum robots. Robotics, IEEE Transactions on. 2006;22(1):43-55.
23. Harvey Lipkin JM, Gary McMurray, Debao Zhou, Wayne Daley. Endoscope Kinematics. 12th IFToMM World Congress; 2007 June 18-21; Besançon.
24. Murray RM, Li Z, Sastry SS, Sastry SS. A Mathematical Introduction to Robotic Manipulation: Taylor & Francis; 1994.
25. Gao G, Penney G, Ma Y, Gogin N, Cathier P, Arujuna A, et al. Registration of 3D trans-esophageal echocardiography to X-ray fluoroscopy using image-based probe tracking. Medical image analysis. 2012 Jan;16(1):38-49.
26. Umeyama S. Least-squares estimation of transformation parameters between two point patterns. Pattern Analysis and Machine Intelligence, IEEE Transactions on. 1991;13(4):376-80.
27. Bavalia N, Anis A, Benz M, Maldjian P, Bolanowski PJ, Saric M. Esophageal perforation, the most feared complication of TEE: early recognition by multimodality imaging. Echocardiography (Mount Kisco, NY). 2011 Mar;28(3):E56-9.

List of tables:

TABLE I. ORIENTATION AND DISTANCE ERRORS OF THE MANIPULATOR SYSTEM

Axes	**Orientation error** (mean$\pm$std)	**Position error** (mean$\pm$std)
Left-right steering	$0.46° \pm 0.18°$	$0.71mm \pm 0.45mm$
Anteflex-retroflex steering	$0.82° \pm 0.51°$	$1.00mm \pm 0.82mm$
Handle rotation	$1.27° \pm 0.44°$	$0.89mm \pm 0.37mm$
Handle translation	$0.57° \pm 0.34°$	$0.32mm \pm 0.15mm$

TABLE II. ORIENTATION AND DISTANCE ERRORS OF THE FORWARD KINEMATIC MODEL

Axes	**Orientation error** (mean$\pm$std)	**Position error** (mean$\pm$std)
Left-right steering	$2.80° \pm 1.15°$	$2.02mm \pm 1.30mm$
Anteflex-retroflex steering	$4.30° \pm 2.12°$	$3.17mm \pm 1.27mm$

List of figures:

Fig. 1. Degrees of freedom of the TEE probe. The four degrees of freedom controlled by the robot are (a) the depth in the esophagus, (b) the rotation about the shaft, (c) left-right steering of the tip and (d) anteflexion-retroflexion of the tip.

Fig. 2. Components of the robotic system designed in CAD software. (a) The handle control mechanism, (b) the rotation mechanism, (c) the translation mechanism.

Fig. 3. Final implementation of the TEE robotic system with the TEE probe clipped in. (a) Handle control structure with all electronics built in, (b) gear train for rotation mechanism, (c) linear belt for translation mechanism, (d) original TEE probe clipped in, (e) control box for other electronics.

Fig. 4. Implementation of the handle control device with all the electronics built in (The cover with a battery pack inside is not shown).

Fig. 5. TEE probe tip bending geometry. (a) The perspective view of the bending tip. (b) The projection view in the bending plane.

Fig. 6. Diagram of transformations from the nano-CT coordinates to the ultrasound image coordinates.

Fig. 7. Coordinate definitions of the TEE probe tip: the bending section and the rigid section.

Fig. 8. Experimental setup to measure the repeatability performance of the TEE robotic system. (a) TEE robotic system, (b) rigid tracking body.

Fig. 9. Experimental setup for the targeted accuracy measurement of the forward kinematic model. (a) TEE robotic system, (b) the rigid section of the TEE probe tip with the rigid tracking body attached, (c) the Optotrak pointer, (d) the rigid reference body, (e) the TEE probe flexible shaft, which was constrained onto a stand, (f) the control laptop of the robot. The Optotrak measurement sensor and the Optotrak control devices and PC are not shown.

Fig. 10. FOV of the TEE is a pyramid shaped structure which can be defined from any TEE volume. Ten planes were selected within the TEE FOV which were parallel to the transducer of the TEE probe.

Fig. 11. Comparison of the measured positions (red dotted line) from the Optotrak system and the predicted positions from the forward kinematic model (blue dotted line).

Fig. 12. Mean distance error of the defined landmarks in the ultrasound image (left-right steering axis).

Fig. 13. Mean distance error of the defined landmarks in the ultrasound image (anteflex-retroflex steering axis).